Final Project Report - ONR Grant N00014-91-J-1433

Characterization of 3D Fault-Generated Seafloor Topography

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Summary of Completed Project

The long-range goal of this study is to understand how tectonic faulting affects the nature, morphology, and composition of the oceanic crust. In particular we seek to determine the effects of seafloor spreading rate and ridge-axis segmentation on the 3D characteristics of seafloor faults and fault-generated topography. During this award period, we achieved three project objectives: 1) we developed new statistical methods of extracting fault geometric information from multi-beam bathymetric data; 2) we developed 2D and 3D fault models that determine the kernel relationship between fault-generated topography and subsurface fault variables; and 3) we quantitatively characterized the style of tectonic faulting in the ONR Atlantic natural laboratory using the newly developed analytical techniques. These results are summarized below and are detailed in the publications listed.

1) Extraction of 3D Fault Information from Multi-Beam Data

We developed a new method of identifying faults from multi-beam bathymetric data using a curvature, rather than slope, analysis technique [Shaw, *Nature*, 1992; Shaw and Lin, *JGR*, 1993]. In this analysis, the seafloor bathymetry is first segmented into small circular patches; the curvature of each patch is then approximated by a best-fitting quadratic surface in a linear least-square sense. When combined with a running-window technique, this curvature method can effectively distinguish fault scarps from slopes of constructional volcanic features.

We applied the curvature and slope methods successfully to the Sea Beam data collected along the Mid-Atlantic Ridge axis between 23°-31°, producing fault maps for the entire area [Shaw and Lin, *JGR*, 1993]. The results show that faults are more linear and more closely spaced at mid-portion of a spreading segment. Towards segment offsets, however, the faults become oblique and the fault spacing increases. This along-axis variability testifies the strong control of ridge segmentation and crustal thickness on styles of faulting [Sempere, Lin et al., *MGR*, 1993; Lin and Bergman, *JGR*, submitted].

In addition to the along-axis variability, there exists additional across-axis asymmetry near segment boundaries. Crust at "inside" corners are more elevated than "outside" corners; residual gravity anomalies also indicate that the inside-corner crust is consistently thinner than the outside-corner crust [Escartin and Lin, *JGR*, 1995]. Such across-axis asymmetry and its off-axis variability may be explained by long-lived detachment faulting and cyclic magmatic/amagmatic extension at slow-spreading ridges [Tucholke and Lin, *JGR*, 1994; Lin et al., *Nature*, in prep.].

2) Determination of Relationship between Topography and Subsurface Fault Variables

Through boundary-element numerical modeling, we determined the precise kernel functions between surface expressions of faults, e.g., topography and gravity, and subsurface fault variables, such as fault depth, dip-angle, and lithosphere thickness. The developed models consider both 2D [Escartin and Lin, *JGR*, 1995] and 3D [Katzman, ten Brink, and Lin, *JGR*,

1995; Shaw and Lin, *JGR*, submitted; Lin and Chen, *GRL*, submitted; ten Brink, Katzman, and Lin, *JGR*, submitted] fault geometries. We applied the kernel techniques in studying the Sea Beam bathymetry of the Mid-Atlantic Ridge and are successful in predicting the main characteristics of ridge-crest morphology and residual gravity. We also studied the effects of variable lithosphere viscosity on long-term survival of seafloor topography [Freed, Lin et al., *Geology*, in press].

Numerical modeling has yielded two important results: 1) Style of faulting is a strong function of local crustal thickness and spreading rate. Small, closely-spaced faults are predicted at fast-spreading ridges, hotspot-influenced ridges, and mid-points of long slow-spreading segments of thick crust. In contrast, large, widely spaced faults are predicted for slow-spreading segments of thin crust [Shaw and Lin, *JGR*, submitted]; 2) The gravity anomaly of individual normal faults at the Mid-Atlantic Ridge is predicted to be less than ~20 mgal for reasonable subsurface fault variables. Therefore although faulting is sufficient to produce the observed *across-axis* asymmetry in crustal elevation and gravity near ridge-axis offsets, it alone is insufficient to explain the *along-axis* "bull eyes" gravity anomalies that are as much as ~50 mgal along some segments of the Mid-Atlantic Ridge [e.g., Lin et al., *Nature*, 1990; Lin and Phipps Morgan, *GRL*, 1992].

3) Quantification of Tectonic Faults in the ONR Atlantic Natural Laboratory

We analyzed multi-beam bathymetry, HMR1 side-scan sonar, gravity, and magnetic data that we collected in the ONR Atlantic natural laboratory at 25.5°-27°N. The ONR Acoustic Reverberation corridor encompasses off-axis traces of nine spreading segments in 0-28 Ma crust, all bounded by non-transform offsets. We identified several new tectonic features in the region, including 1) Strong contrasts in seafloor elevation, faulting style, and crustal thickness between off-axis continuations of inside- vs. outside-corner crust; 2) Close-contoured, "boudin-shaped" gravity lows along off-axis continuations of segment centers, suggesting long-term (3-9 m.y.) magmatic pulses in the Mid-Atlantic Ridge [Lin, et al., *EOS*, 1993, 1995; *Nature*, in prep.]; 3) Strong correlations between abyssal hill morphology, e.g., RMS highs, and gravity-derived crustal thickness [Goff et al., *JGR*, in press]; and 4) Fast-propagating rifts in a slow-spreading environment [Tucholke, et al., *EOS*, 1995; *MGR*, in prep.].

Publications Supported by this Award

1) Papers Published in Refereed Journals (11 Total)

Escartin, J., and J. Lin, Ridge offsets, normal faulting, and gravity anomalies of slow-spreading ridges, *Journal of Geophysical Research, 100, 6163-6177,* 1995.

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Ito, G., and J. Lin, Mantle temperature anomalies along the present and paleo-axes of the Galapagos spreading center as inferred from gravity analyses, *Journal of Geophysical* Research, *100, 3733-3745,* 1995.

Lin, J., and J. Phipps Morgan, The spreading rate dependence of three-dimensional mid-ocean ridge gravity structure, *Geophysical Research Letters, 19,* 13-16, 1992.

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2) Papers In Press or Submitted to Refereed Journals (7 Total)

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Goff, J.A., B.E. Tucholke, J. Lin, G.E. Jaroslow and M.C. Kleinrock, Quantitative analysis of abyssal hills in the Atlantic ocean: A correlation between crustal thickness and extensional faulting, *Journal of Geophysical Research,* in press, 1995.

Lin, J., and J. Y. Chen, Subsurface and surface loadings on the young oceanic lithosphere at the northern Mid-Atlantic Ridge, *Geophysical Research Letters,* submitted.

Lin, J., and E.A. Bergman, Rift grabens, seismicity, and volcanic segmentation of a slow-spreading ridge: the Mid-Atlantic Ridge between the Kane and Atlantis transform faults, *Journal of Geophysical Research,* submitted.

Shaw, W.T., and J. Lin, Models of oceanic ridge lithospheric deformation: Dependence on crustal thickness, spreading rate, and segmentation, *Journal of Geophysical Research,* submitted.

Smith, D.K., J.R. Cann, M.E. Dougherty, J. Lin, S. Spencer, C. Macleod, J. Keeton, E. McAllister, R. Pascoe, B. Brooks, and S. Wanda, Mid-Atlantic Ridge volcanism from deep-towed side-scan sonar images, 25°-29°N, *Journal of Volcanology and Geothermal Research,* in press, 1995.

ten Brink, U., R. Katzman, and J. Lin, Three-dimensional models of deformation near strike-slip faults, *Journal of Geophysical Research,* submitted.

3) Invited Papers in Non-Refereed Journals (5 Total)

Fujimoto, H, W.B. Bryan, K. Kobayashi, H. Kinoshita, M. Tivey, P. Kelemen, A. Takeuchi, T. Matsumoto, H. Ishizuka, T. Furata, T. Fujiwara, J. Lin, H. Hotta, and G.M. Purdy, Diving and surface surveys of the western part of the Kane transform fault, *InterRidge News, 3,* 20&27, 1994.

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Lin, J., R. Searle, and J. Sinton, Segmentation and fluxes at mid-ocean ridges, In: *Reports of the InterRidge Meso-Scale Symposium and Workshops,* edited by H. Sloan, pp. 4-40, the InterRidge Office, Durham, UK, 1994.

Lin, J., J. Karson, and J. Sinton, Design workshop for experimental approaches to ridge segment structure and dynamics (RISES), *RIDGE Workshop Rep.,* Woods Hole, Massachusetts, 24 p., 1995.

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5) Invited Presentations at Conferences (10 Total)

Kleinrock, M.C., B.E. Tucholke, and J. Lin, The trace of non-transform offsets and the evolution of Mid-Atlantic Ridge spreading segments between 25°25' and 27°10'N over the past 30 m.y., *EOS Trans. AGU, 73*, 538, 1992.

Lin, J., and J.Y. Chen, Lithospheric deformation near spreading segments along the Mid-Atlantic Ridge 24°-31°N: Observation and models, *EOS Trans. AGU, 72*, 260, 1991.

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Lin, J., B.E. Tucholke, M.C. Kleinrock, and J.A. Goff, Variations in crustal faulting and magmatic accretion along the Mid-Atlantic Ridge and off-axis: Results from the western flank of the MAR at 25°25'-27°10'N, *EOS Trans. AGU, 73*, 538, 1992.

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Smith, D.K., J.R. Cann, M.E. Dougherty, J. Lin, B. Brooks, S. Spencer, C.J. MacLeod, E. McAllister, R.A. Pascoe, and J.A. Keeton, Volcanism and faulting on the inner valley floor of the Mid-Atlantic Ridge (24-30°N), *EOS Trans. AGU, 73*, 568, 1992.

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Escartin, J., and J. Lin, Gravity constraints on the style of crustal thinning at the Mid-Atlantic Ridge, *EOS Trans AGU, 74*, 664, 1993.

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Spencer, S., J. Lin, D.K. Smith, J.R. Cann, E.McAllister, R. Pascoe, M. E. Dougherty, S. Garland, C.J. MacLeod, and J.A. Keeton, Nature of non-transform offsets on the Mid-Atlantic Ridge between 24 and 30°N, *EOS Trans. AGU, 73*, 553, 1992.

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7) Graduate Students Supported Under This Award (4 Total)

Javier Escartin, MIT-WHOI Joint Program in Oceanography
Garrett Ito, MIT-WHOI Joint Program in Oceanography
William Shaw, MIT-WHOI Joint Program in Oceanography
Andrew Freed, WHOI Guest Student and Graduate Student at University of Arizona